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**TITLE:     CLOCK GRID SKEW REDUCTION TECHNIQUE  
              USING BIASABLE DELAY DRIVERS**

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# CLOCK GRID SKEW REDUCTION TECHNIQUE USING BIASABLE DELAY DRIVERS

## Background of Invention

[0001] As shown in Figure 1, a typical computer system (10) has, among other components, a microprocessor (12), one or more forms of memory (14), integrated circuits (16) having specific functionalities, and peripheral computer resources (not shown), e.g., monitor, keyboard, software programs, etc. These components communicate with one another via communication paths (19), e.g., wires, buses, etc., to accomplish the various tasks of the computer system (10).

[0002] In order to properly accomplish such tasks, the computer system (10) relies on the basis of time to coordinate its various operations. To this end, a crystal oscillator (18) generates a reference clock signal (referred to and known in the art as “system clock” and shown in Figure 1 as **sys\_clk**) to various parts of the computer system (10). However, modern microprocessors and other integrated circuits typically operate at frequencies significantly higher than that of the signals most crystal oscillators can provide, and thus, another clock source, such as a phase locked loop (“PLL”) (20) is used to phase align the reference clock with an internally generated clock of the PLL (20). It follows that one of the main objectives of high speed microprocessor design is to properly distribute a clock signal, e.g., a chip clock (shown in Figure 1 as **chip\_clk**), from a source, e.g., PLL (20), to clock controlled elements in the microprocessor.

[0003] Figure 2 shows a clock distribution network (22) for a microprocessor (12). A reference clock (shown in Figure 2 as **ref\_clk**), generated from outside the microprocessor (12), serves as an input to a PLL (20). Essentially, the PLL (20) uses the reference clock to generate a high frequency clock signal, i.e., a chip clock, and then uses feedback to maintain a specific phase relationship between its

output, the chip clock (shown in Figure 2 as **chip\_clk**), and the reference clock. The chip clock from the PLL (20) is then distributed to one or more clock headers/buffers (17) that distribute the chip clock to a global clock grid (21). The global clock grid (21) feeds the chip clock to another set of clock headers/buffers (18) that distribute the chip clock to, for example, local clock grids (24) and a feedback loop (26) that feeds the chip clock back to the PLL (20). Further, the local clock grids (24) feed the chip clock to base components of the microprocessor (12), such as latches (23) and flip-flops (28).

[0004] As a clock signal, such as the chip clock shown in Figure 2, propagates to the various parts and components of a microprocessor, one or more types of system variations may alter the behavior and/or integrity of the clock signal. Common system variations include, but are not limited to, capacitive noise, inductive noise, voltage variations, temperature variations, process variations, unbalanced wire loads, and RC wire delays. Due to these and other variations across a microprocessor, a particular clock signal may arrive at different clock controlled elements of the microprocessor at different times. This difference in the arrival of a clock signal at different clock controlled elements is referred to and known in the art as “skew.”

[0005] Generally, skew is defined as the difference in the arrival time of a particular signal's active edge at two different clock controlled elements. In other words, skew results when the delay from a common source through two different paths connected to two different clock controlled elements is not matched. For example, in Figure 3a, a global clock grid header (17) outputs a clock signal (shown in Figure 3a as **clk\_0**) that propagates to two different paths (32, 34) within a global clock grid (21 in Figure 2). The first path (32) is subject to a first delay (36) and the second path (34) is subject to a second delay (38). The first and second delays (36, 38) may be induced by various variations across an integrated circuit. The first delayed clock signal (shown in Figure 3a as **clk\_1**) serves as an

input to a first local clock grid header (18), and the second delayed clock signal (shown in Figure 3a as **clk\_2**) serves as an input to a second local clock grid header (18). Because the first delay (36) and second delay (38) may not be equal, the first and second local clock grid headers (18) are clocked, i.e., triggered, at different times in spite of the expectation that they should be clocked at the same time due to synchronous system design as exemplified by the common data inputs (shown in Figure 3a as **data**) to elements (40, 42) controlled by the clock signal outputs from the first and second local clock grid headers (18).

[0006] Figure 3b shows a timing diagram of the circuit shown in Figure 3a. The first delayed clock signal (represented in Figure 3b as **clk\_1**) has a first delay (44) with respect to the global clock grid header (17) generated clock signal (represented in Figure 3b as **clk\_0**). The second delayed clock signal (represented in Figure 3b as **clk\_2**) has a second delay (46) with respect to the global clock grid header (17) generated clock signal. As shown in Figure 3b, the first delay (44) and second delay (46) are not equal, and thus skew results (48) between the first delayed clock signal and the second delayed clock signal.

[0007] Due to skew, elements that are designed to synchronously operate with a clock signal instead function off different time references—a generally undesirable effect. In the case of a min-time situation, i.e., where there is a race between a data signal and a clock signal to some latching point, the presence of skew among the min-time paths may effectively cause a particular integrated circuit to become unusable. Notwithstanding the expensive and undesirable effects of such min-time skew, skew, in a general sense, may cause, among other things, performance degradation, inaccurate operation, and malfunction.

### Summary of Invention

[0008] According to one aspect of the present invention, an integrated circuit

comprises a clock source that outputs a clock signal, where the clock signal propagates down a first path; and a first biasable delay driver that inputs the clock signal at a point on the first path, where the first biasable delay driver is selectively sized based on a delay of the clock signal from the clock source to the point on the first path.

[0009] According to another aspect, an integrated circuit comprises means for propagating a clock signal from a clock source to a point on a signal path; and means for inputting the clock signal at the point and outputting a delay biased clock signal based on a delay of the clock signal from the clock source to the point.

[0010] According to another aspect, a method for reducing clock skew comprises determining a first delay of a clock signal from a clock source to a point on a first path, where the clock signal propagates from the clock source to the point on the first path; and selectively sizing a first biasable delay driver depending on the first delay, where the first biasable delay driver inputs the clock signal at the point on the first path.

[0011] According to another aspect, a computer system comprises a processor; a memory; and instructions, residing in the memory and executable by the processor, for: determining a first delay of a clock signal from a clock source to a point on a first path, wherein the clock signal propagates from the clock source to the point on the first path; and selectively sizing a first biasable delay driver depending on the first delay, wherein the first biasable delay driver inputs the clock signal at the point on the first path.

[0012] According to another aspect, a computer-readable medium, having recorded therein instructions executable by processing, comprises instructions for: determining a first delay of a clock signal from a clock source to a point on a first path, wherein the clock signal propagates from the clock source to the point on the

first path; and selectively sizing a first biasable delay driver depending on the first delay, wherein the first biasable delay driver inputs the clock signal at the point on the first path.

[0013] Other aspects and advantages of the invention will be apparent from the following description and the appended claims.

### **Brief Description of Drawings**

[0014] Figure 1 shows a typical computer system.

[0015] Figure 2 shows a typical clock distribution network.

[0016] Figure 3a shows a portion of a clock grid that induces skew.

[0017] Figure 3b shows a timing diagram in accordance with the portion of the clock grid shown in Figure 3a.

[0018] Figure 4a shows a portion of a clock grid that is subject to unbalanced loading induced skew.

[0019] Figure 4b shows a portion of a clock grid that is subject to RC wire delay induced skew.

[0020] Figure 5a shows a circuit in accordance with an embodiment of the present invention.

[0021] Figure 5b shows a circuit in accordance with another embodiment of the present invention.

[0022] Figure 5c shows a biasable delay driver in accordance with the embodiments shown in Figures 5a and 5b.

[0023] Figure 5d shows a timing diagram in accordance with an embodiment of the present invention.

[0024] Figure 6 shows a flow process in accordance with an embodiment of the

present invention.

[0025] Figure 7 shows a flow process in accordance with an embodiment of the present invention.

[0026] Figure 8 shows a computer system in accordance with an embodiment of the present invention.

### Detailed Description

[0027] Two types of skew inducing behavior are unbalanced loading and RC wire delays. Figure 4a shows a portion of a clock grid that is subject to unbalanced loading induced skew. In Figure 4a, the global clock grid header (17) outputs a signal that propagates to two different loaded paths (52, 54) within a global clock grid. Each path's load is formed by a resistive component and a capacitive component. The first loaded path (52) experiences some resistance (56) and capacitance (58) (shown in Figure 4a as C). The second loaded path (54) also experiences some resistance (60) and capacitance (62) (shown in Figure 4a as C'). Because it is extremely difficult to equally divide the load among the various paths of the clock grid, there is a likely probability that the load of the first loaded path (52) and the load of the second loaded path (54) are not equal, i.e., are "unbalanced." This can be more clearly evidenced by the fact that the first loaded path (52) is subject to a gate capacitance of one local clock grid header (18), whereas the second loaded path (54) is subject to the gate capacitances of two local clock grid headers (18).

[0028] Such unbalanced loading among the two loaded paths (52, 54) results in a difference in delays between the global clock grid header (17) output (shown in Figure 4a as x) and the local clock grid header (18) input (shown in Figure 4a as y) at the end of the first loaded path (52) and between the global clock grid header (17) output and the local clock grid headers' (18) inputs (shown in Figure 4a as z)

at the end of the second loaded path (54). Thus, due to this difference in delay, skew results between the clock signal at the input of the local clock grid header (18) at the end of the first loaded path (52) and the clock signal at the inputs of the local clock grid headers (18) at the end of the second loaded path (54). This skew propagates, in turn, to the local clock grids and various clock controlled elements.

[0029] The second type of skew induced behavior results from RC wire delay on the clock grid. This type of skew occurs due to the failure to match the lengths of paths connecting a clock source to clock controlled element dependent on the clock source output. In other words, if the wire lengths of two paths connecting a clock source output to two different clock controlled elements are not the same, the additional resistance and capacitance contributed by the mismatch on the longer path results in skew.

[0030] Figure 4b shows a portion of a clock grid that is subject to RC wire delay induced skew. In Figure 4b, the global clock grid header (17) outputs a signal that propagates to a first local clock grid header (18) and a second clock local clock grid header (18). However, as shown in Figure 4b, the length of the path from the global clock grid header (17) output (shown in Figure 4b as **a**) to the first local clock grid header (18) input (shown in Figure 4b as **b**) is not equal to the length of the path from the global clock grid header (17) output to the second local clock grid header (18) input (shown in Figure 4b as **c**).

[0031] Thus, the path from the global clock grid header (17) output to the first local clock grid header (18) input experiences an RC delay that is a function of a first resistance (76) and a first capacitance (78), whereas the path from the global clock grid header (17) output to the second local clock grid header (18) input experiences an RC delay that is a function of the first resistance (76), a second resistance (80), the first capacitance (78), and a second capacitance (82). Because the paths to the first local clock grid header (18) and the second local clock grid



header (18) experience different RC delays, skew results between the signals at the first local clock grid header (18) input and the second local clock grid header (18) input. This skew propagates, in turn, to the local clock grids and various clock controlled elements.

[0032] To improve performance and reduce skew, the present invention uses a biasable delay driver to compensate for skew on a clock grid that is induced by unbalanced loading and RC wire delays. Thus, embodiments of the present invention relate to a biasable delay driver that is used to reduce clock grid skew that is induced by unbalanced loading. Embodiments of the present invention further relate to a biasable delay driver that is used to reduce skew induced by RC wire delay. Embodiments of the present invention further relate to a method for reducing unbalanced load induced skew. Embodiments of the present invention further relate to a method for reducing RC wire delay induced skew. Embodiments of the present invention further relate to a method for tuning a driver using determined minimum and maximum delay amounts.

[0033] Figure 5a shows a circuit in accordance with an embodiment of the present invention. In Figure 5a, the global clock grid header (17) outputs a signal to two different loaded paths (92, 94), where each path is subject to a different RC load as shown by the fact that the first loaded path (92) experiences an RC load formed by some resistance (96) and capacitance (98) (shown in Figure 5a as C) whereas the second loaded path (94) experiences an RC load formed by some other resistance (100) and capacitance (102) (shown in Figure 5a as C'). Because this unbalanced loading results in skew between the signal at the end of the first loaded path (92) end (shown in Figure 5a as y) and the signal at the end of the second loaded path (94) end (shown in Figure 5a as z), biasable delay drivers (104, 106, 108) are positioned at the ends of the first loaded path (92) and second loaded path (94). A detailed discussion of the biasable delay drivers is discussed below with reference to Figure 5c.

[0034] Figure 5b shows a circuit in accordance with another embodiment of the present invention. In Figure 5b, the global clock grid header (17) outputs a signal to two different path ends (shown in Figure 5b as **b** and **c**), where one path is longer than the other. Thus, effectively, the path to the first path end is subject to an RC delay that is a function of a first resistance (112) and a first capacitance (114), whereas the path to the second path end is subject to an RC delay that is a function of the first resistance (112), a second resistance (116), the first capacitance (114), and a second capacitance (118). Because this RC delay mismatch results in skew between the signal at the first path end and the signal at the second path end, biasable delay drivers (120, 122) are positioned at the first and second path ends. A detailed discussion of the biasable delay drivers is discussed below with reference to Figure 5c.

[0035] Figure 5c shows a biasable delay driver (130) in accordance with the embodiments shown in Figures 5a and 5b. The biasable delay driver (130) is formed by a biasable delay NAND gate (132) followed by an inverter (134) having a fixed size. Thus, as shown in Figure 5c, the size of the NAND gate (132) may be changed by varying  $W_p$ , i.e., the width of the PMOS transistor, and/or by varying  $W_n$ , i.e., the width of the NMOS transistor, of the NAND gate (132), whereas the  $W_p$  and  $W_n$  of the inverter (134) is fixed. Thus, the biasable delay driver (130) is characterized to different delays by changing the size of the NAND gate (132). Consequently, the biasable delay driver (130) may be used to compensate for a fast path by sizing down the size of the biasable delay driver (130). Alternatively, the biasable delay driver (130) may be used to compensate for a slow path by sizing up the biasable delay driver (130).

[0036] For example, if a first path is subject to a delay that is longer than a delay experienced by a second path, then one of the following remedial measures may be taken to reduce, or eliminate, skew resulting from the mismatched delay: (1) sizing up a biasable delay driver at the end of the first path, i.e., the slower path,

(2) sizing down a biasable delay driver at the end of the second path, i.e., the faster path, or (3) sizing up a biasable delay driver at the end of the first path and sizing down a biasable delay driver at the end of the second path.

[0037] Those skilled in the art will appreciate that because a fixed size inverter (134) is used at the output of the biasable delay driver (130), the configuration of the biasable delay driver (130) allows for the compensating of skew without changing the drive strength of the biasable delay driver (130). Further, those skilled in the art will appreciate that other embodiments may use a biasable delay driver having equivalent logic functionality.

[0038] To further illustrate the function and use of a biasable delay driver, Figure 5d shows a timing diagram in accordance with an embodiment of the present invention. Figure 5d shows timing waveforms for a first pre-biased clock signal (represented in Figure 5d as **x\_prebiased**) and a second pre-biased clock signal (represented in Figure 5d as **y\_prebiased**). The first pre-biased clock signal and the second pre-biased clock signal may be signals residing at the inputs of two different clock controlled elements that are designed to operate synchronously with respect to a particular clock signal. However, due to unbalanced loading, RC wire delay, or some other delay inducing behavior, there is a relatively large amount of skew (140) between first pre-biased clock signal and the second pre-biased clock signal. This skew (140) is a direct result of the difference in delay along the path ending with the first pre-biased clock signal and along the path ending with the second pre-biased clock signal.

[0039] The timing diagram in Figure 5d shows several ways to reduce or eliminate the skew between the first and second pre-biased clock signals using one or more biasable delay drivers (not shown). In one embodiment, a sized down biasable delay driver may be used to input the first pre-biased clock signal and output a first delay biased clock signal (represented in Figure 5d as **x\_biased**), where active

edges of the first delay biased clock signal arrive after a point in time when the active edges of the first pre-biased clock signal would have arrived if the sized down biasable delay driver had not been used. By slowing down the first delay biased clock signal relative to the first pre-biased clock signal, the skew (142) between the first delay biased clock signal and the second pre-biased clock signal is reduced relative to the amount of skew (140) between the first and second pre-biased clock signals.

[0040] In another embodiment, a sized up biasable delay driver may be used to input the second pre-biased clock signal and output a second delay biased clock signal (represented in Figure 5d as **y\_biased**), where active edges of the second delay biased clock signal arrive before a point in time when the active edges of the second pre-biased clock signal would have arrived if the sized up biasable delay driver had not been used. By speeding up the second delay biased clock signal relative to the second pre-biased clock signal, the skew (144) between the first pre-biased clock signal and the second delay biased clock signal is reduced relative to the amount of skew (140) between the first and second pre-biased clock signals.

[0041] In another embodiment, a sized down biasable delay driver and a sized up biasable delay driver may be used in conjunction with each other. In this embodiment, the sized down biasable delay driver generates the first delay biased clock signal, where the first delay biased clock signal has been slowed down relative to the first pre-biased clock signal. The sized up biasable delay driver generates the second delay biased clock signal, where the second clock signal has been sped up relative to the second pre-biased signal. Using this approach, the amount of skew (146) between the first and second delay biased clock signals is even further reduced.

[0042] In order to determine whether a biasable delay driver needs to be biased, a determination may be made as to whether a particular amount of delay necessitates

the tuning of the biasable delay driver. To this end, Figure 6 shows an exemplary flow process in accordance with an embodiment of the present invention. Initially, the amount of delay present from a clock source to an input of a biasable delay driver is determined (step 150). This determination may be made using simulated circuit measurements, simulation runs, etc. Next, a determination is made as to whether the determined amount of delay is less than a minimum delay (step 152). The minimum delay is discussed below with reference to Figure 7.

[0043] If the determined amount of delay is less than the minimum delay, the biasable delay driver size is decreased by one unit (step 154) in order to slow down the signal output from the biasable delay driver. Thereafter, the flow process repeats itself from step 150.

[0044] If the determined amount of delay is not less than the minimum delay, a determination is made as to whether the determined amount of delay is greater than or equal to a maximum delay (step 156). The maximum delay is discussed below with reference to Figure 7.

[0045] If the determined amount of delay is greater than the maximum delay, the biasable delay driver size is increased by one unit (step 158) in order to speed up the signal output from the biasable delay driver. Thereafter, the flow process repeats itself from step 150. However, if the determined amount of delay is not greater than the maximum delay, then the biasable delay driver is determined to be adequately biased (step 160).

[0046] Referring now to the exemplary flow process shown in Figure 7, to determine the maximum and minimum delays, the delays along the paths from the clock source to the clock controlled elements are determined (step 170). If the longest path delay minus the shortest path delay is greater than one gate delay (one gate delay is the range of biasable delay of a particular biasable delay driver) (step 172), the minimum delay is set to be equal to the longest path delay minus one

gate delay (step 174). However, if the longest path delay minus the shortest path delay is not greater than one gate delay (step 172), the minimum delay is set to be equal to the shortest path delay (step 176). In either case, the maximum delay is set to be equal to the minimum delay plus the minimum increment resulting from tuning a biasable delay driver (step 178).

[0047] For example, consider that the longest path delay is 200ps, the shortest path delay is 170ps, one gate delay is 20ps, and the minimum increment resulting from tuning the biasable delay driver is 2ps. Thus, initially, skew between a clock signal at the end of longest path and the clock signal at the end of the shortest path is 200ps – 170ps, or 30ps. Using the flow process shown in Figure 7, because the longest path delay minus the shortest path delay, 30ps, is longer than one gate delay (step 172), 20ps, the minimum delay is set to be equal to the longest path delay minus one gate delay (step 174), i.e., 200ps – 20ps, or 180ps. Because the minimum increment resulting from tuning the biasable delay driver is 2ps, the maximum delay is set to be equal to the minimum delay plus the minimum biasable delay driver increment (step 178), i.e., 180ps + 2ps, or 182ps. It follows that based on the newly determined minimum and maximum delays, the skew, using one or more biasable delay drivers, is forced to be between 180ps and 182ps, i.e., a skew less than or equal to 2ps. Thus, skew is reduced from 30ps to 2ps.

[0048] Those skilled in other embodiments, in the case that the longest path delay minus the shortest path delay is greater than one gate delay, the minimum delay may be set to be equal to any value between the shortest path delay and the longest path delay depending on the range of sizes of available biasable delay drivers.

[0049] In other embodiments, if the difference in path delays between two paths is too large to effectively compensate for skew using one or more biasable delay drivers, a dummy load may be positioned at the end of the shorter delay path in order to reduce the difference in the path delays between the two paths.

[0050] Those skilled in the art will appreciate that one will have a larger range of choice of precision with more available differently sized biasable delay drivers.

[0051] Figure 8 shows an exemplary computer system (180) in accordance with an embodiment of the present invention. Input parameters (182) may include a circuit schematic or layout of a particular circuit that needs to be improved with respect to skew. Input parameters (182) may also include information regarding the range of sizes of available biasable delay drivers.

[0052] The input parameters (182) serve as input data to the computer system (180) via some computer-readable medium, e.g., network path, floppy disk, input file, etc. The computer system (180) then stores the input parameters (182) in memory (not shown) to subsequently determine (via microprocessor functions) a longest path delay and shortest path delay of the circuit (184). The computer system (180) may also determine gate delay information and biasable delay driver size increment information (184). Using this information (184), the computer system (180) may then determine the maximum and minimum delays for the circuit (186). Thereafter, using the maximum and minimum delay information (186), the computer system (180) outputs, via some user-readable medium, e.g., monitor display, network path, etc., the appropriate size(s) of biasable delay driver(s) (188) that need to be used in the circuit in order to effectively reduce or eliminate skew present in the circuit. The computer system (180) may additionally output a modified circuit schematic that incorporates the selected biasable delay drivers.

[0053] Those skilled in the art will appreciate that in other embodiments, a software program capable of generating appropriate biasable delay driver sizes consistent with the various techniques presented in the present invention may be used.

[0054] Advantages of the present invention may include one or more of the

following. In some embodiments, because a biasable delay driver may be used to modulate a clock signal, skew between two clock signals may be reduced or eliminated.

[0055] In some embodiments, because a biasable delay driver compensates for skew-procuring delay on a path, unbalanced loading induced skew among two or more paths may be reduced or eliminated.

[0056] In some embodiments, because a biasable delay driver compensates for skew-procuring delay on a path, RC wire delay induced skew among two or more paths may be reduced or eliminated.

[0057] In some embodiments, because skew may be reduced or eliminated using one or more biasable delay drivers, circuit performance is improved.

[0058] In some embodiments, because a biasable delay driver compensates for a difference in delay between two paths, a designer does not need to focus on equalizing loads on the two paths.

[0059] In some embodiments, because a biasable delay driver has a fixed size element at its output, a drive strength of the biasable delay driver may remain constant even when the biasable delay driver is biased.

[0060] In some embodiments, because wire delays may be biased using biasable delay drivers, there is no need to match wire lengths within an integrated circuit; thus, there is less wire, which, in turn, leads to less capacitance, which, in turn, leads to less power consumption.

[0061] In some embodiments, because wire delays may be biased using biasable delay drivers, wire delays may be easily matched by interchanging one or more biasable delay drivers; thus, reducing the need for rerouting and/or creating additional wire tracks and/or needing different biasable delay drivers.

[0062] While the invention has been described with respect to a limited number of



embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.